

Two Point Correlation Technique for the Measurements of Poloidal Plasma Rotation by Heavy Ion Beam Probe^{*)}

Leonid ELISEEV, Alexander MELNIKOV, Stanislav PERFILOV and Carlos HIDALGO¹⁾

Institute of Tokamak Physics, NRC "Kurchatov Institute", 123182, Moscow, Russia

¹⁾*Association EURATOM-CIEMAT, 28040, Madrid, Spain*

(Received 9 December 2011 / Accepted 3 April 2012)

The paper proposes a method to measure poloidal rotation velocity of toroidal plasma v_{pol} using Heavy Ion Beam Probe (HIBP) with a multi-slit energy analyzer. The method is based on calculation of phase shift between broadband density turbulence measured simultaneously in two sample volumes, located at the same magnetic surface but separated poloidally. Oscillatory component of HIBP beam current is used as a density turbulence characteristic. HIBP is capable to provide the temporal evolution of the v_{pol} in a fixed radial position and also the v_{pol} profile by periodic radial scan. Method was verified in real plasma experiment in ECRH and NBI discharges on the TJ-II stellarator. Result shows that in low density discharges ($n_e \approx 0.3\text{-}0.5 \times 10^{19} \text{ m}^{-3}$) absolute values of local v_{pol} is about 4-6 km/s, oriented in the ion diamagnetic drift direction. When HIBP operates for radial scans, it is conventionally measuring the plasma potential profile, and so provides the radial electric field E_r and velocity of $E \times B$ drift ($v_{E \times B}$) at the same time as plasma rotation. Experimental data shows that in low density ECRH plasma the rotation velocity coincides with $E \times B$ velocity within achieved experimental accuracy. When the density is increasing, both $v_{E \times B}$ and v_{pol} tends to decrease and then change the sign at threshold plasma densities in the range of $n_e \approx 0.7\text{-}1 \times 10^{19} \text{ m}^{-3}$. With this new proposed technique HIBP becomes the new effective tool to study plasma rotation and turbulence characteristics in toroidal plasmas.

© 2012 The Japan Society of Plasma Science and Nuclear Fusion Research

Keywords: HIBP, turbulence, poloidal rotation velocity

DOI: 10.1585/pfr.7.2402064

1. Introduction

Broadband density turbulence in the frequency range 0-250 kHz was studied on TJ-II stellarator ($R = 1.5 \text{ m}$, $\langle a \rangle = 0.22 \text{ m}$, $B_0 = 1 \text{ T}$, $n_e = 0.3\text{-}6 \cdot 10^{19} \text{ m}^{-3}$) in the bulk plasma by Heavy Ion Beam Probe (HIBP) [1] with two-slit energy analyzer [2]. Sample volumes (SV) determined by two slits were located on the same magnetic surface and separated poloidally by 1-2 cm, except the central area, $\rho < 0.3$. SV positions and sizes were determined by beam trajectory calculations. HIBP dual detector line for two-slit measurements is shown on Fig. 1. HIBP secondary beam current I_{tot} is proportional to local electron density multiplied by attenuation factor [3]:

$$I_{\text{tot}} = 2I_{\text{prim}}\sigma^{12}\lambda_{\text{SV}}n_{\text{SV}} \times \exp \left\{ - \int_{P1}^{\text{SV}} n(\rho)\sigma^{12}(\rho)dl - \int_{\text{SV}}^{P2} n(\rho)\sigma^{23}(\rho)dl \right\},$$

where I_{prim} is the primary beam current, λ_{SV} is the sample volume length, n_{SV} is the local density at SV, σ^{12} and σ^{23} are the effective cross-sections of electron impact ionization from Cs^+ to Cs^{+2} and from Cs^{+2} to Cs^{+3} correspondingly.

author's e-mail: reonid@yahoo.com

^{*)} This article is based on the presentation at the 21st International Toki Conference (ITC21).

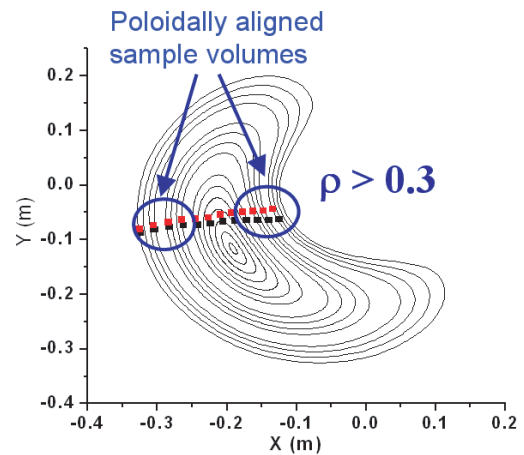


Fig. 1 HIBP dual detector line. Red and black squares correspond to the sample volumes for the first and the second slits. Blue areas indicates the parts of detector line where sample volumes are oriented poloidally.

For the typical TJ-II discharges the path integral effect [4] is negligible since no global long wave modes with $k_r < 2\pi/a$ have been found so far. So, fluctuations of I_{tot} are proportional to the local n_e fluctuations [2]:

$$\frac{\tilde{n}_e}{n_e} \approx \frac{\tilde{I}_{\text{tot}}}{I_{\text{tot}}}$$

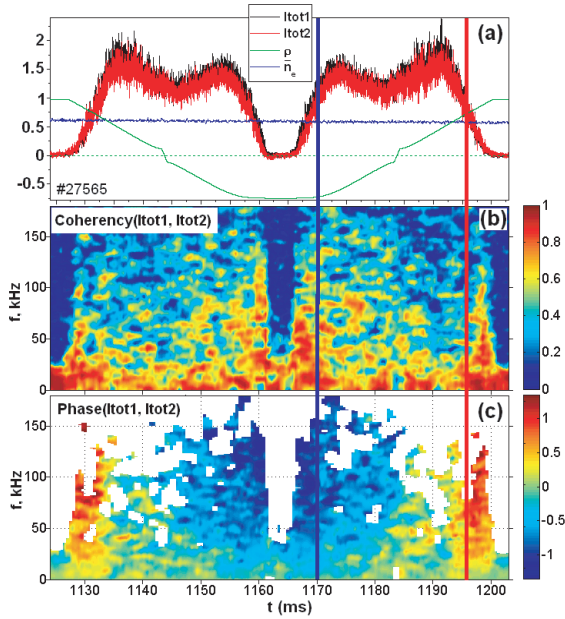


Fig. 2 Two HIBP secondary beam current profiles, from two SV, obtained simultaneously by beam radial scan (a), their coherency (b) and cross-phase (c) spectrograms. Green curve in (a) denotes the SV radial position. Note the passing of SV from Low Field Side (LFS) to the High Field Side (HFS) via the plasma axis.

Both I_{tot} signals for each SV were analyzed with two-point correlation technique, coherency and cross-phase $\theta_{1,2}$ were determined and the phase velocity of fluctuations $v_{\text{phase}} = \Delta x \cdot 2\pi f / \theta_{1,2}$ was calculated. This technique was first used to investigate the power of fluctuations as a function of frequency and wave-number in the direction of edge Langmuir probes measurements [5].

HIBP measurements were performed in ECRH and NBI heated plasmas ($P_{\text{ECRH}} = 400\text{-}500\text{ kW}$, $P_{\text{NBI}} = 600\text{ kW}$).

An example of the HIBP measurements is presented in Fig. 2, which shows two I_{tot} signals: $I_{\text{tot}1}$ and $I_{\text{tot}2}$ (a), their coherency (b) and cross-phase (c). The radial profiles of the I_{tot} for both SVs are identical, which proves the location of the SVs at the same magnetic surfaces (the radial difference in SV positions $\Delta\rho_{1,2} < 0.02$). The properties of fluctuations (i.e. frequency spectra, poloidal phase shift and poloidal coherence) for two time intervals marked by blue ($t_1 = 1170\text{ ms}$) and red ($t_2 = 1197\text{ ms}$) vertical lines in Fig. 2 are shown on Fig. 3. Coherency was calculated by 2048 samples (per 2 ms) with Hann window of length 256 samples. High coherency (> 0.5) is observed in the frequency range $0 < f \leq 130\text{ kHz}$. Figure 2 (b) shows that dependence of cross-phase on frequency is close to the linear one in the frequency range $0 < f \leq 80 \div 100\text{ kHz}$. This fact means that phase velocity v_{phase} is approximately the same for this wide frequency range of the broadband turbulence. This linear dependence may be interpreted as the plasma poloidal rotation as a solid body with $v_{\text{pol}} = \langle v_{\text{phase}} \rangle$.

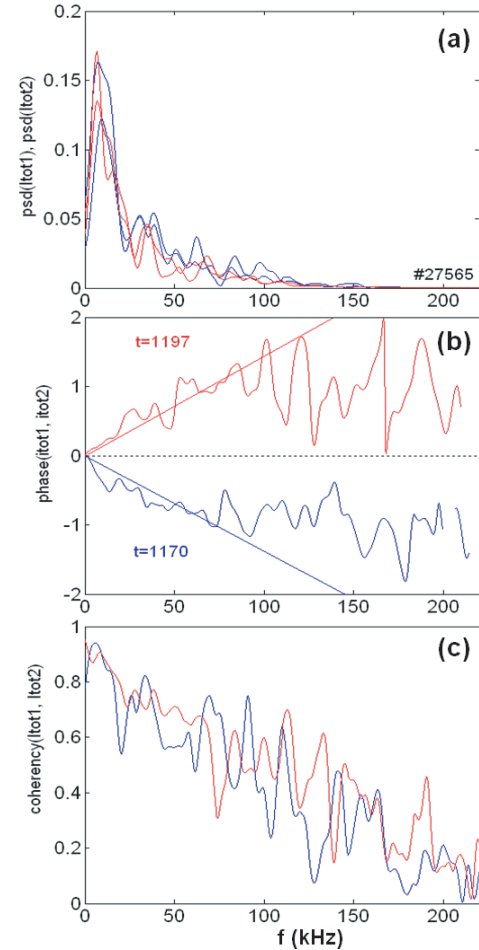


Fig. 3 Power spectrum density of $I_{\text{tot}1}$, $I_{\text{tot}2}$ (a), cross-phase (b) and coherency (c) of HIBP secondary currents at $t = 1170\text{ ms}$ (blue) and $t = 1197\text{ ms}$ (red). There is a high coherency at $0 < f < 130\text{ kHz}$.

2. Radial Scan Measurements

HIBP radial profile measurements are performed by scanning the sample volumes along the detector line by changing voltage on the sweeping plates. Whereas potential profile measurements can be measured in time scales in the order of $t_{\text{scan}} = 5\text{-}15\text{ ms}$, the profile of v_{pol} needs significantly longer scan time $t_{\text{scan}} = 30\text{-}60\text{ ms}$ to obtain satisfactory statistics for cross-phase calculation. It means that radial profile of v_{pol} can be measured only in steady state plasma, $t_{\text{scan}} < t_{\text{steady-state}}$.

Figure 4 shows the radial profile of v_{pol} measured in steady ECRH plasma with plasma densities in the range of $n_e \approx 0.57 \times 10^{19}\text{ m}^{-3}$. Results show a reversal in the phase relation between $I_{\text{tot}1}$ and $I_{\text{tot}2}$ signals in LFS and HFS regions, consistent with a poloidal plasma rotation velocity in the ion diamagnetic drift direction.

3. Temporal Evolution

Figure 5 shows the temporal evolution of v_{pol} in a fixed point $\rho \approx 0.6$. In the ECRH stage ($t = 1080\text{-}1110\text{ ms}$) of

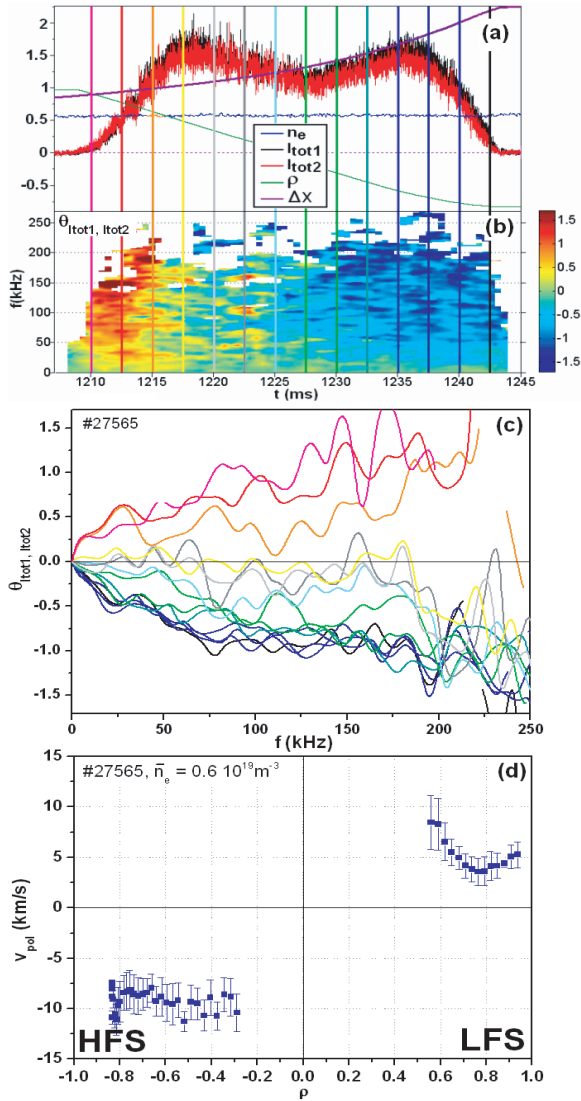


Fig. 4 HIBP currents (a), cross-phase (b) (c) and profile of v_{pol} (d). Rotation is directed to ion diamagnetic drift.

the discharge ($P_{\text{ECRH}} = 0.4 \text{ MW}$), where the line averaged density is about $n_e \approx (0.4-0.5) \times 10^{19} \text{ m}^{-3}$ and the plasma potential as well as the radial electric field is positive [6, 7]. Poloidal rotation, as deduced from the two-point correlation technique, is directed to ion diamagnetic drift with values in the order of 4 km/s. In the pure NBI stage ($t = 1110-1160 \text{ ms}$) of discharge ($P_{\text{NBI}} = 0.58 \text{ MW}$) the plasma density increases, plasma potential and electric field become negative [8, 9]. In these conditions poloidal velocity changes the direction from ion to electron diamagnetic drift with values up to 10 km/s, which is consistent with previous results using Doppler reflectometry [10].

4. Comparison of v_{pol} with $v_{\text{E} \times \text{B}}$

TJ-II HIBP is conventionally used for the potential profile studies [6–9]. When HIBP is operated for radial scans, it measures the plasma potential profile, and so pro-

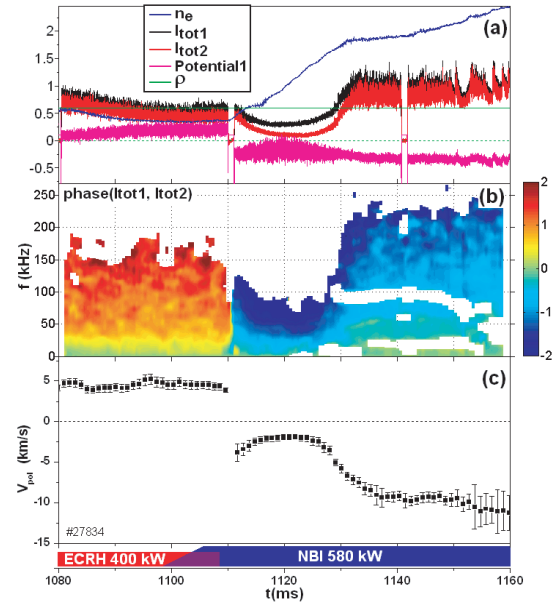


Fig. 5 Time evolution of the v_{pol} (LFS, $\rho \approx 0.6$). In NBI phase growth of n_e causes the plasma potential to become negative and the poloidal rotation to change direction to electron diamagnetic drift.

vides the radial electric field E_r during one shot [11].

The trajectory optimization has allowed us to measure profiles of poloidal velocity and plasma potential at the same time (using slow-scan technique in a steady state, $t_{\text{scan}} = 30-60 \text{ ms}$). Such mode of HIBP operation gives us a possibility to compare local values of v_{pol} and $v_{\text{E} \times \text{B}}$.

Note that both values are retrieved from the same set of the raw HIBP data: v_{pol} from the cross-phase of the density, $v_{\text{E} \times \text{B}}$ from potential profile. This experiment can be performed in special experimental conditions of long steady state plasma. Figure 6 shows the results of such experiment in ECRH discharge ($P_{\text{ECRH}} = 0.5 \text{ MW}$, $n_e = 0.45 \times 10^{19} \text{ m}^{-3}$). The upper box (a) presents the raw profiles of two HIBP potentials and currents, which are practically equal for the first and second slits. This remarkable similarity is considered as an experimental proof of the proper poloidal adjustment of two SVs. The figure shows that the local values of $v_{\text{E} \times \text{B}}$ and v_{pol} present a reasonably good agreement in the direction and value within the experimental errors. Radial electric field errors are estimated by variation of the fitting parameters, leaving potential fit within experimental errors for the specific scan.

5. Conclusions

Multi-slit HIBP shows a possibility to study poloidal rotation of plasma. Measurements of v_{pol} were done in ECRH and NBI heated plasmas in the TJ-II stellarator. The possibility to measure profiles of v_{pol} and electric potential at the same time was shown in the steady state discharges. Local values of v_{pol} and $v_{\text{E} \times \text{B}}$, both measured by HIBP, are similar within the experimental error.

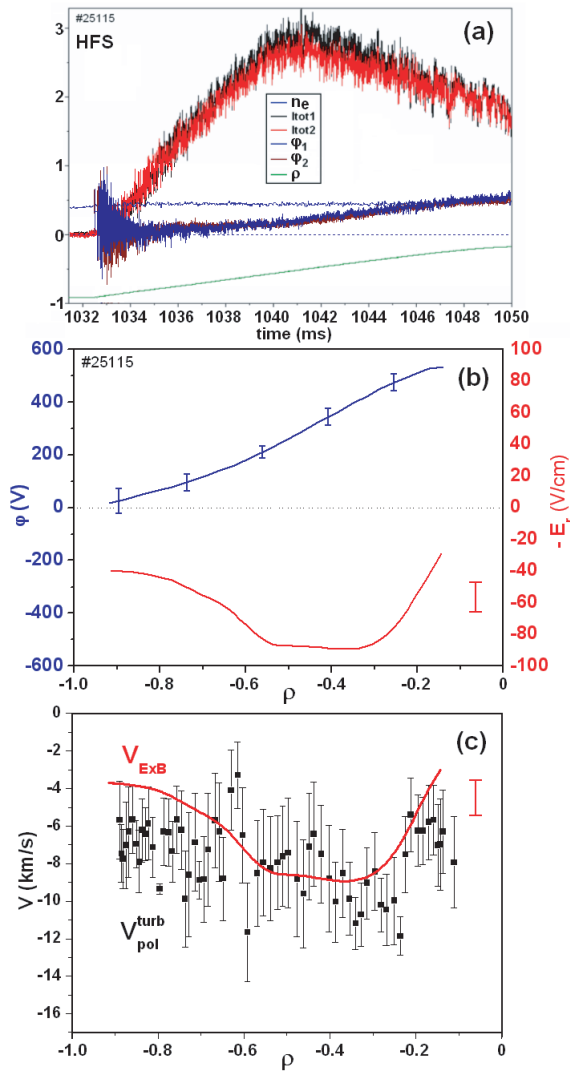


Fig. 6 Comparison of v_{pol} and v_{ExB} measured by HIBP. (a) raw signals of HIBP currents and potentials obtained during radial scan. The density time trace is in blue, the SV radial position is in green. (b) smoothed potential (blue) and E_r (red) radial profiles, (c) v_{pol} and v_{ExB} radial profiles. Both of v_{pol} and v_{ExB} are directed to ion diamagnetic drift.

The work was supported by RFBR grants 10-02-01383 and 11-02-00067.

- [1] I.S. Bondarenko *et al.*, Rev. Sci. Instrum. **72**, 583 (2001).
- [2] A.V. Melnikov *et al.*, Nucl. Fusion **50**, 084023 (2010).
- [3] Yu.N. Dnestrovskij *et al.*, IEEE Trans. Plasma Sci. **22**, 310 (1994).
- [4] J.W. Heard *et al.*, Rev. Sci. Instrum. **64**, 1001 (1993).
- [5] Ch.P. Ritz *et al.*, Phys. Fluids **27**, 2956 (1984).
- [6] A.V. Melnikov *et al.*, Fusion Sci. Technol. **46**, 299 (2004).
- [7] A.V. Melnikov *et al.*, Czech. J. Phys. **55**, 1569 (2005).
- [8] A.V. Melnikov *et al.*, Fusion Sci. Technol. **51**, 31 (2007).
- [9] A.V. Melnikov *et al.*, Nucl. Fusion **51**, 083043 (2011).
- [10] T. Happel *et al.*, EPL **84**, 65001 (2008).
- [11] L.I. Krupnik *et al.*, Czech. J. Phys. **55**, 317 (2005).